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Effects of temperature and suction on the stiffness of unsaturated soil under cyclic loads

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BRIEF INTRODUCTION, METHODOLOGY AND KEY RESULTS

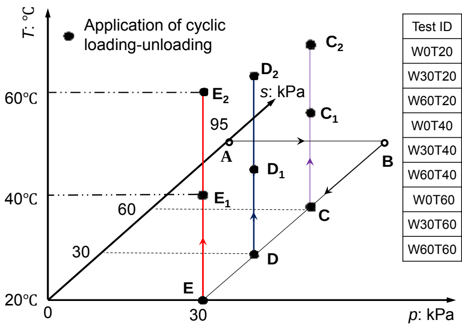
In the field of geo-energy (e.g., energy geo-structure and radioactive waste disposal), soils are often subjected to various temperature and suction conditions (Laloui and Di Donna, 2013). A fundamental understanding of thermal and suction effects on soil stiffness is therefore essential for predicting ground movement and dynamic response of geo-structures at the working condition. Up to now, many theoretical and experimental studies have demonstrated that soil behaviour is highly dependent on suction and temperature (e.g., Romero et al., 2003; François and Laloui, 2008). Most of these studies, however, focused on soil behaviour under monotonic loading. Thermal and suction effects on soil behaviour under cyclic loads are not fully understood.

To investigate thermal and suction effects on soil stiffness under cyclic loads, a series of cyclic triaxial tests were carried out on compacted silt, using a temperature and suction contolled triaxial system developed by Ng and Zhou (2014). In total, nine tests were conducted at three suctions of 60, 30 and 0 kPa. At each suction level, three tests were carried out at different temperatures (20, 40 and 60°C). Each test consists of four stages: isotropic compression, wetting, heating and cyclic loading-unloading. Figure 1 shows stress paths of all tests at the first three stages. The purposes of these three stages were to control the stress, suction and temperature of soil specimen, respectively. After equalization of stress, suction and temperature, each specimen was subjected to cyclic loading and unloading. Cyclic deviator stress in haversine form was applied, while net confining pressure was maintained constant at 30 kPa. Four levels of cyclic stress (30, 40, 55 and 70 kPa) were applied to each specimen in succession, with 100 cycles at each cyclic stress.

Figure 2 shows soil stress-strain relationship measured during a typical 100-cycle triaxial test. For clarity, only the first and last 10 cycles are presented in the figure. During the first 10 cycles, soil plastic strain accumulates with increasing number of cycles. During the last 10 cycles, there is no obvious additional accumulation of plastic strain, implying that the soil specimen has reached a stable reversible response. From soil stress-strain relationship at the stable state, secant Young's modulus of soil is calculated at each suction and temperature condition.

Figure 3(a) illustrates the influence of temperautre on Young's modulus at suction of 60 kPa. At each cyclic stress, Young's modulus decreases by about 20% as temperature increases from 20 to 60°C. The reduction of Young's modulus with increasing temperature is very likely due to the fact that yield stress of unsaturated soil decreases with an increase of temperature (thermal softening) (François and Laloui, 2008). Given a smaller yield stress and over-consolidaiton ratio (OCR), soil specimen would behave softer. Figure 3(b) shows thermal effects on Young's modulus at suction of 30 kPa. It is clear that at this suction level, Young's modulus also decreases consistently with an increase of temperature. The reduction of Young's modulus with an increase of temperature suggests that any design based on parameters measured at room temperature would underestimate soil deformation, when soil temperature in the field is significantly higher than room temperature.

Figure 3(c) shows thermal effects on Young's modulus at zeor suction. As soil temperature increases from 20 to 60°C, Young's modulus increases by about 5% at lower cyclic stress (30 and 40 kPa) but decreases by about 5% at higher cyclic stress (55 and 70 kPa). Comparisons between Figures 3(a) through 3(c) reveal that thermal effects on resilient modulus are more significant at suctions of 60 and 30 kPa than that at zero suction. On the other hand, comparisons clearly illustrate that Young's modulus is strongly affected by soil suction. At the same temperature, resilient modulus increases by more than twofold when suction increases from 0 to 60 kPa.



Test ID	Stress paths
W0T20	A→B→E
W30T20	A→B→D
W60T20	A→B→C
W0T40	A→B→E→E$_1$
W30T40	A→B→D→D$_1$
W60T40	A→B→C→C$_1$
W0T60	A→B→E→E$_2$
W30T60	A→B→D→D$_2$
W60T60	A→B→C→C$_2$

Fig. 1. Stress paths of temperature and suction controlled cyclic triaxial tests

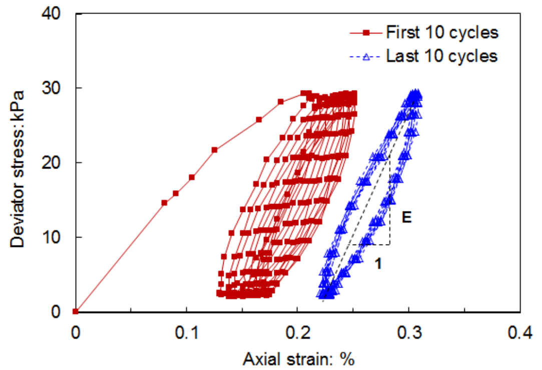


Fig. 2. Typical response of unsaturated soil under cyclic loading and unloading

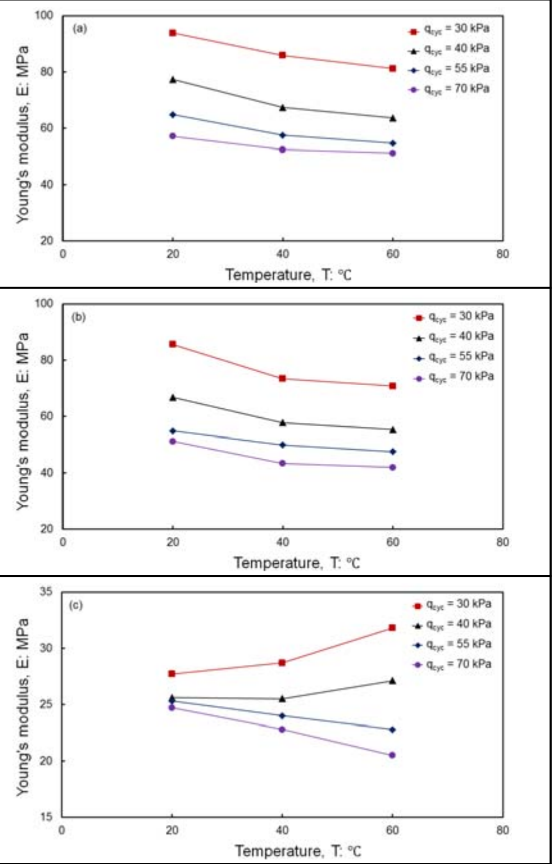


Fig. 3. Thermal effects on Young's modulus at suctions of: (a) 60 kPa; (b) 30 kPa; (c) 0 kPa

KEY CONCLUSIONS

Thermal effects on Young's modulus of the silt under cyclic loads are more significant at suctions of 60 and 30 kPa than that at zero suction. At suctions of 60 and 30 kPa, as soil temperature increases from 20 to 60°C, Young's modulus decreases by about 20%. This observation implies that any design based on parameters measured at room temperature would underestimate soil deformation, when soil temperature in the field is significantly higher than room temperature

Young's modulus is significantly affected by soil suction. At a given temperature, resilient modulus increases by more than twofold when suction increases from 0 to 60 kPa.

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